# Quality Control of Cement Deep Soil Mixing Work for the Port of Oakland Projects

David S. Yang
*Raito, Inc., San Leandro, California*

Christopher J. Coutu
*Geomatrix Consultants, Oakland, California*

Larry L. Scheibel
*Geomatrix Consultants, Oakland, California*

Proceedings: Fifth International Conference on Case Histories in Geotechnical Engineering
New York, NY, April 13-17, 2004

# QUALITY CONTROL OF CEMENT DEEP SOIL MIXING WORK FOR THE PORT OF OAKLAND PROJECTS

**David S. Yang**
Raito, Inc.
San Leandro, CA-USA-94577

**Christopher J. Coutu**
Geomatrix Consultants
Oakland, CA-USA- 94612

**Larry L. Scheibel**
Geomatrix Consultants
Oakland, CA-USA- 94612

**ABSTRACT**

The Cement Deep Soil Mixing (CDSM) method is an in situ soil treatment technology that introduces and mixes cementitious materials with native soils using hollow-stem rotating shafts equipped with a cutting tool at the tip and mixing paddles above the tip. The successful use of the soil-cement produced by CDSM relies on the selection of acceptance criteria and construction quality control during the in situ soil mixing process. Two CDSM projects for the Port of Oakland are used as case examples to present the acceptance criteria set and the execution of the quality control program for the soil mixing work. This quality control program ensures that the geometric and material design parameters of the CDSM structure have been obtained. The data acquired from these two projects are presented and compared with strength data from two other projects to illustrate the influence of acceptance criteria over the CDSM products.

## INTRODUCTION

CDSM is an in situ soil mixing method that reinforces soft ground by producing soil-cement structures or elements in versatile configurations. The equipment, installation, and quality control procedures of this deep mixing method are derived from that originally developed by the Port and Airport Research Institute of Japan for stabilization of soft marine deposits and are different from the soil mixing methods derived from the soil mix wall method used in the U.S. (Yang, 2003) since 1987. The construction of a soil-cement grid wall in 1999 along Berths 55/56 at the Port of Oakland for slope stabilization and reduction of lateral spreading potential was the first application of the CDSM soil treatment operation in the United States (Herlache et al. 1999). Since 1999, the CDSM method has been used to produce approximately 500,000 m$^3$ of soil-cement in the western hemisphere. Major applications included the production of soil-cement wall, grid, and block configurations designed for the mitigation of potential liquefaction and lateral spreading, improvement of bearing capacity, and control of settlement on petroleum refinery, commercial wharf, and roadway construction projects.

In 2001, the CDSM method was used for ground stabilization at two major projects for the Port of Oakland: 1) Berths 57/58 Project, and 2) Oakland Airport Roadway Project. At Berths 57/58, loose sandy fills and soft Bay Mud were treated to form a soil-cement buttress to provide a stable shoreline under static loading conditions and to limit lateral deformations for earthquake loading. At the airport, loose sandy fills and soft Bay Mud were improved by CDSM to form soil-cement foundations and soil-cement gravity retaining structures for the construction of grade separation structures.

The successful use of the soil-cement produced by the CDSM relies on the selection of acceptance criteria and construction quality control during the in situ soil mixing process. This paper presents the procedures used in these two Port of Oakland projects to insure that the CDSM equipment, installation procedures, and mix design would produce the soil-cement wall, grid, and block with required geometry, strength, and uniformity to meet the design intent.

## PORT OF OAKLAND PROJECTS

### Berths 57/58 Project, Port of Oakland, California

This project involved the widening of the existing Inner Harbor Channel and the construction of a container wharf above a new 19.5 meter deep shoreline cut slope to accommodate large container ships. The container terminal at Berths 57 and 58 includes 900 m of new wharf structure and approximately 526,000 m$^2$ of yard facility. CDSM was the method specified for improving loose sandy fill and soft Bay Mud deposits at the site. A soil-cement buttress (CDSM grid) was constructed along the shoreline to maintain the stability of the cut slope and to limit lateral deformations under earthquake loading conditions.

### Subsurface Conditions

The generalized subsurface conditions encountered along the site of the wharf structure consist of fill; recent bay sediments/channel infill deposits, including normally consolidated Young Bay Mud; Merritt/Posey Sand; and overconsolidated Old Bay Mud. The fill stratum consists of 1 to 2 m of mixed gravel, sand, and clay fill underlain by loose to medium dense clayey or silty sand fill with lenses or layers of Bay Mud fill. Interfingered soft to very soft Bay Mud and loose to medium dense clayey sand deposits were encountered below the fill and extended to about 10 to 12 m along most of the site. However, near the west end of the wharf at Berth 57, a deep channel filled with sediments was encountered extending to depths of up to 27 m. This channel is filled with Bay Mud, loose to medium dense clayey sands, medium stiff sandy clays, and dense cemented silty sands. Underlying the recent bay sediments is the Merritt/Posey Sand of the San Antonio Formation consisting of dense to very dense, fine to medium grained sand and clayey sand. The Merritt/Posey Sand is underlain by a stratum of stiff to very stiff silty clay, which is referred to locally as Old Bay Mud. Groundwater levels vary with tidal fluctuations and are generally between 1 to 3 m below ground surface.

Design of CDSM Soil Improvement Schemes

CDSM was used to treat the existing soils in situ to create a reinforced soil embankment capable of providing a stable shoreline (Geomatrix Consultants, 2000).

The in situ soil mixing created a grid or cellular system of soil-cement walls parallel to the shoreline, in which unimproved materials were enclosed within the treated walls of each cell. The soil-cement grid is expected to cause the entire zone to act as a gravity structure and resist lateral deformations during design level seismic shaking. In addition, the grid is also expected to limit strain and may mitigate the loss of soil strength due to liquefaction for the unimproved soils within the CDSM cells. However, for the analysis of earthquake loading conditions, the loose sands were considered to have strength appropriate for liquefied soil conditions. The CDSM treatment was extended through the Bay Mud and keyed 600 mm into the Merritt/Posey sand to form soil-cement grid. In the shallow Bay Mud area, the grid consisted of two longitudinal walls spaced at 9.5 m connected by transverse walls spaced at 3.6 m, on center, as shown in Fig. 1a. In the deep Bay Mud area, the width of the CDSM embankment was increased by extending the transverse walls in the direction of the shoreline slope. When the width of the CDSM embankment was greater than 20.5 m, a third longitudinal wall was added as indicated in Fig. 1b. The maximum treatment depth in the deep Bay Mud area was 26.8 meters.

Oakland Airport Roadway Project, Oakland, California

The construction of Oakland Airport Roadway for the airport expansion required the stabilization of subsurface soils for the construction of three grade separation structures, two at interchanges and one at an intersection of roadways serving the airport. Loose sandy fills and soft Bay Mud were improved by CDSM for the construction of soil-cement foundations under the MSE wall of a roadway overcrossing, and for the installation of soil-cement gravity retaining walls of a roadway undercrossing. In both cases, the soil-cement

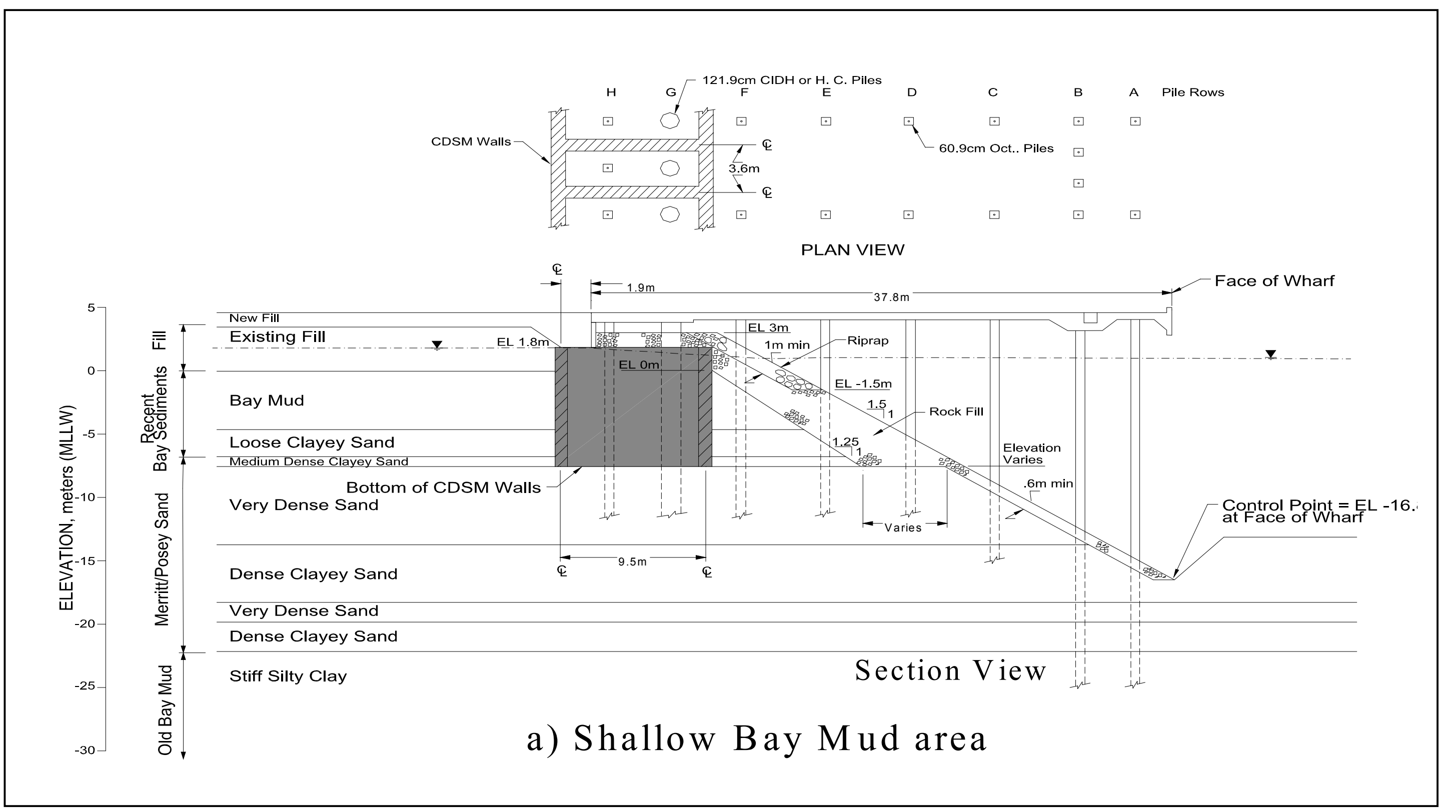


*Fig. 1a. Cross Section of CDSM, Shallow Bay Mud Area, Berths 57/58, Port of Oakland*

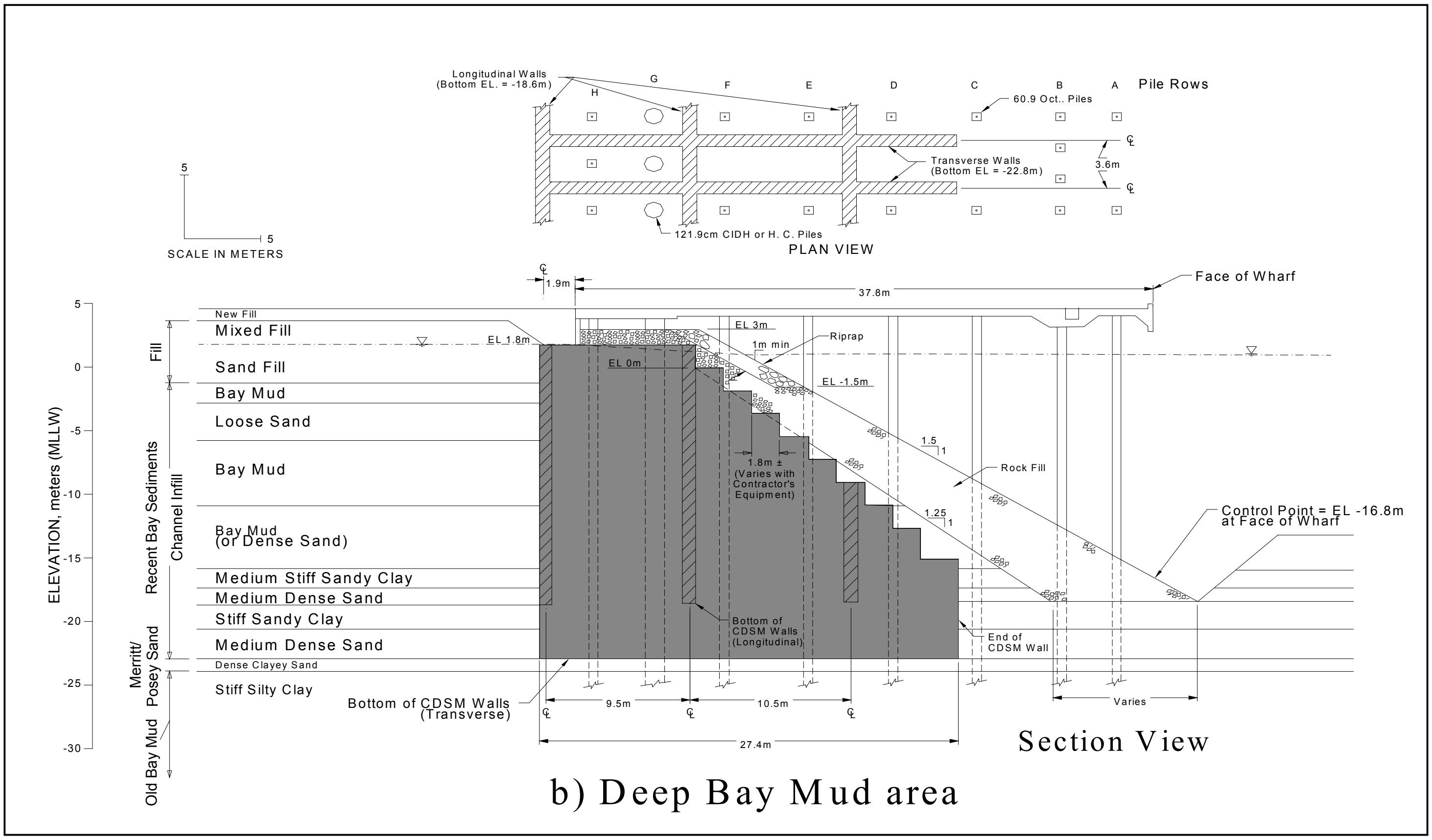


*Fig. 1b. Cross Section of CDSM, Deep Bay Mud Area, Berths 57/58, Port of Oakland*

was used to provide a stable foundation/retaining structure under static loading conditions and limit the lateral deformations under earthquake loading. CDSM was also used to construct two cutoff walls for groundwater control. The CDSM work consisted of soil-cement walls or soil-cement-bentonite walls constructed by in situ soil mixing. Individual soil-cement-bentonite walls (CDSM cutoff walls) were used to provide permanent seepage control. A block-type treatment pattern was used to provide permanent retaining structures to resist both static and seismic loads and to limit the potential for lateral spreading of the earth embankments during seismic loading conditions (Yang, et al. 2001).

## Subsurface Conditions

The airport site is located on former tidelands or shallow water areas reclaimed from the bay by filling.

The generalized subsurface conditions encountered within the upper 30 m below the existing ground surface in the vicinity of the roadway project consist of artificial fill, Young Bay Mud and the San Antonio Formation. The artificial fill is generally less than 4.5 m thick and includes hydraulically placed dredged sand materials, which are often found in a loose or very loose condition below the water table. The thickness of the Young Bay Mud is generally less than 3 m and consists of soft to very soft silty clay. Underlying the Young Bay Mud are competent clays and sands of the San Antonio Formation. The ground water levels generally vary from depths of about 1.5 m to 3 m below the existing ground surface.

## Design of CDSM Soil Improvement Schemes

CDSM soil improvement was used at each of the three grade separation structures in the airport roadway project. At the Doolittle Drive/Airport Drive interchange, a single-row CDSM cutoff wall was formed by overlapping mixing shafts with a diameter of 90 cm to provide permanent seepage control as well as to minimize dewatering requirements during construction. At the Airport Drive/Air Cargo Road interchange, a block-type treatment of overlapping columns was used to improve the strength of existing soil beneath a proposed new soil embankment to reduce the potential for lateral spreading of the embankment under seismic loading conditions. This treatment pattern was also used at the Air Cargo Road/Taxiway B intersection to provide a permanent retaining structure and to function as part of a temporary shoring system during construction. This treatment area also included a CDSM cutoff wall to provide permanent seepage control and reduce dewatering requirements during construction. The CDSM soil improvement scheme was designed to limit the permanent lateral deformation of the embankment to 150 mm during the design level earthquake. Typical cross sections through the soil-cement foundation under the MSE wall and the soil-cement gravity retaining wall are presented in Fig. 2a and 2b respectively.

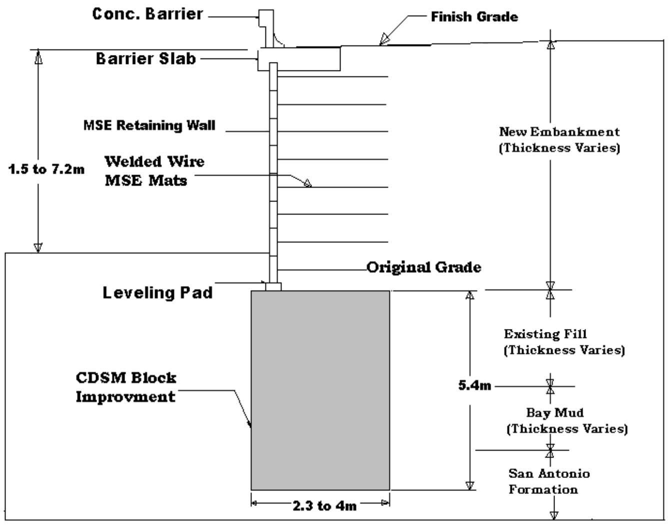


*Fig 2a. CDSM foundation under MSE wall and embankment, Oakland Airport Roadway Project*

CDSM CONSTRUCTION QUALITY CONTROL

Design of soil-cement structures such as the wall, grid, or block type patterns used for the Port of Oakland projects included both geometric design and material design. The geometric design included the treatment ratio, treatment layout, and treatment depth. The material design included the required strength, permeability, and modulus of elasticity of the soil-cement product. Based on the geometric tolerances and material designs, a set of acceptance criteria was established for the CDSM structures. These acceptance criteria were included in the specifications and served as a foundation for the requirements of the production and construction quality control for the CDSM structures. The specifications for these two deep mixing projects mainly consisted of four parts: Acceptance Criteria, Product, Execution, and Construction Quality Control. Construction execution and quality control, according to the specifications, are presented below following a brief review on acceptance criteria and product requirements.

ACCEPTANCE CRITERIA

The CDSM wall, grid, and block patterns were designed to meet the acceptance criteria of geometric tolerances, strength and uniformity.

<u>Geometric Tolerances</u>

To provide clearance for driving adjacent piles and to carry the design loads to the bearing stratum below the loose sandy fill and Bay Mud soils, the horizontal alignment of each soil-cement panel was required to be located within 150 mm of the planned location at the top of the panel. To insure continuity of the soil-cement walls, the adjacent columns overlap by 20 percent of the area of a single column and the vertical

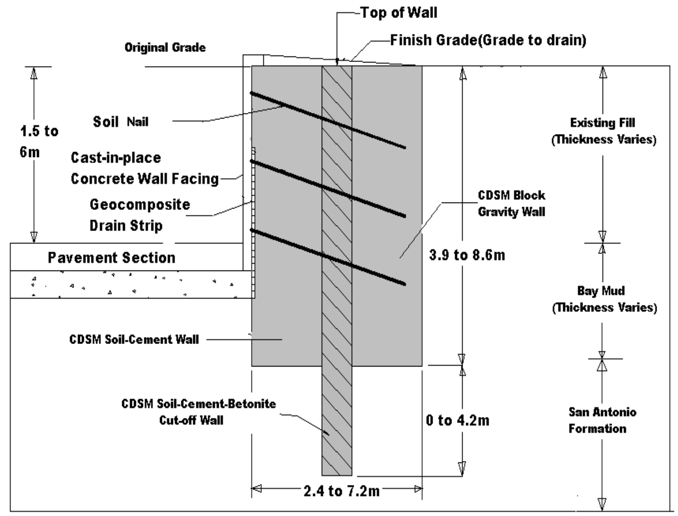


*Fig 2b. CDSM gravity retaining walls and cutoff wall for taxiway undercrossing, Oakland Airport Roadway Project*

inclination of each panel was required to be within 1:100 (horizontal to vertical). The bottom of each panel was required to penetrate at least 300 mm into the competent bearing strata.

<u>Strength</u>

The soil-cement panels were designed to achieve an average unconfined compressive strength of at least 1035 KPa at 28 days and a minimum unconfined compressive strength of 690 KPa, which was 67 percent of the design average. The unconfined compressive strength was used as an index parameter for quality control purposes. Other engineering properties such as compressibility and shear strength were derived from the unconfined compressive strength based on previously established correlations.

The specified strength requirements for the soil-cement will mandate the mix design and mixing procedure of the soil mixing work. Based on previous experience and testing data, an average strength requirement of 1035 KPa (150 psi) will allow for the most efficient production of soil-cement in most soil types except for soils with high water and organic contents. Increasing the required average strength above 1035 KPa would, in general, increase the difficulty and reduce the efficiency of soil mixing. Due to the inherent variation of subsurface soils and the process of core sampling and testing, the strength data of soil-cement scatter more widely than other man-made materials such as concrete. The distribution of the strength data could be represented by either a normal or lognormal distribution curve. To manage the lower range of the strength data for quality control purposes, a required minimum strength can be specified, as for the Port of Oakland projects. As an alternative, a statistical control over the lower range of strength data can be used. The strength data obtained from these two Port of Oakland projects will be compared with data sets obtained from two sites using statistical control to illustrate the influence of specified minimum or lower range strength requirements on the properties of soil-cement produced.

Uniformity

Uniformity of mixing was evaluated based on visual observations of full-depth samples recovered from select soil-cement panels. Lumps of unimproved soils were required to be no more than 20 percent of the total volume of any 1.2 m long section of the continuous full-depth core sample. Any individual or aggregation of lumps of unimproved soil was required to be less than 300 mm. In addition, continuous core recovery of at least 85 percent was required over any 1.2 m core run. Any unrecovered core length was assumed to represent unimproved soil.

PRODUCTS

Materials

Portland Cement Type II was specified to produce a water-based cement grout for mixing with in situ soils. Fresh water was used to manufacture the grout.

Equipment

In order to ensure that adequate equipment was used for soil mixing, the following equipment requirements were imposed: 1) Multi-shaft mixing equipment, with at least two soil mixing shafts, should be used to produce a uniform soil-cement mixture; 2) The soil mixing rig should be equipped with electronic sensors built into the leads to determine vertical alignment; 3) The equipment should allow the engineer to confirm the penetration depth within 150 mm during construction; 4) The grout should be premixed in a mixing plant, using a batch process, which combines dry materials and water in predetermined proportions. Automatic batch scales should be used to accurately determine the mix proportions for the water and cement during grout preparation; 5) Positive displacement pumps should be used to transfer the grout from the mixing plant to the augers. For the uniform initial distribution of grout during soil mixing, the grout should be delivered to each auger by an individual positive displacement pump; 6) To control soil mixing energy, the rig should be equipped with sensors to monitor the mixing tool penetration/withdrawal speed, the mixing tool rotation speed, and the grout injection rate.

Soil-cement Product

The soil-cement panel constituting the wall, grid, and block pattern was required to meet the minimum and average strength requirements based on the testing specimens from each full-depth core sample location.

EXECUTION

Horizontal Alignment

To assure that the soil-cement panels were installed within the 150 mm tolerance of the horizontal locations, the Contractor accurately staked the location of each panel of the CDSM wall, grid, and block structures using a licensed surveyor before beginning the installation. To maintain the continuity, the wall was produced stepwise by overlapping the adjacent outside columns of the previously installed panels. Following the construction, the Contractor submitted as-built drawings indicating the location of the CDSM wall, grid, and block structures in terms of project coordinates.

Vertical Alignment

To maintain a panel inclination within the specified 1:100 (horizontal to vertical) tolerance, the equipment operator adjusted the vertical alignment of the lead, which supports the mixing tool, to within 1:150 throughout the soil mixing process. The verticality was also periodically confirmed by the Contractor's field personnel using optical surveying instruments. In the Deep Bay Mud area along Berths 57/58, adjacent panels greater than 18m in depth were overlapped with one full column diameter (900 mm) to insure wall continuity.

Wall Depth

To assure that soil-cement mixing extended to the required design depths, mixing penetration was measured using an electronic sensor, which was monitored on a real-time basis. As a back-up and confirmation system, the penetration depth was periodically measured using a tape attached to the mast, which indicated the length of the mixing shaft inserted below a reference point. The quality control system of the Contractor also included monitoring the amperage draw of the mixing tool in the various encountered soil layers. The amperage reading was used to confirm adequate penetration into the competent stratum. The final depth of each panel was recorded on the daily quality control report.

Grout Preparation

In order to accurately control the water/cement ratio of the grout, the proportions of water and cement were determined by weight prior to mixing using automatic batch scales. The

Contractor routinely checked the specific gravity of the grout, at least four times per shift. The specific gravity was maintained in the field to within 3 percent of the calculated specific gravity for the mix design. In cases where the measured specific gravity was lower than that required by the design mix, the Contractor added cement, remixed, and retested the grout. To assure accuracy, the Contractor periodically recalibrated the batch scales.

### Soil-Grout Mixing

Installation of each soil-cement panel to the full design depth was generally completed without a break. Where an interruption of more than 1 hour was observed, the panel was remixed along its entire design depth. The grout was pumped from the batch plant through the mixing shafts and injected in situ from the tip of the mixing tool. The mixing tool blended, circulated, and kneaded the soil with the injected grout. Each completed panel was a uniform mixture of grout and in situ soils. Subsequent core sampling of representative panels confirmed that the lumps of unimproved soil were limited to less than 20 percent of the total volume of the wall segment, and individual or aggregate lumps of unimproved soil were less than 300 mm, as required by the project specifications. Having met the acceptance criteria for strength and uniformity, no remixing of a full-depth panel was required for either project.

### Shaft Rotational Speed and Penetration/Withdrawal Rate

The mixing shaft rotational speed and penetration/withdrawal rate were adjusted to provide sufficient mixing energy to achieve adequate uniformity. The required rotational speeds and penetration/withdrawal rates for the various soil layers encountered were determined during the test sections performed at the site prior to the full production. Mixing parameters were modified during the production soil mixing where additional testing verified acceptable results.

### Grout Injection Rate

The grout injection rate per cubic meter of the soil-cement panel was calculated in accordance with the grout-soil mix design. Several trial soil mix designs were established in the laboratory and evaluated during the pre-production test sections. The final mix designs were selected based on the results of the test sections. The Contractor continuously controlled and monitored, on a real-time basis, the volume of grout injection. Injected grout volume was recorded on the daily quality control report. If the volume of grout injected for any 1.2 m vertical segment of a column was less than the amount required to meet the grout-soil ratio established during the test sections, the panel was remixed locally with additional grout. Due to varying subsurface conditions, additional test panels were occasionally installed to obtain data for optimizing the mix designs.

## QUALITY CONTROL PROGRAM

The Contractor's quality control program included: a) installing multiple test sections; b) field monitoring of mixing parameters during the wall construction; c) sampling and testing the completed soil-cement product; and d) preparing of a daily quality control report. The Engineer representing the Owner logged each core, evaluated the uniformity of the soil-cement mix, selected specimens from the recovered cores for testing, and reviewed the quality control reports.

### Sample Collection and Strength Testing

In addition to the geometric requirements, the acceptance of the soil-cement produced was based on demonstrating that the soil-cement had met the strength and uniformity requirements. Verification on the strength and uniformity was determined based on observation of the full-depth continuous sampling and on strength testing of the representative core samples. For evaluation of the soil-cement cutoff wall, cast samples prepared from discrete wet sampling were used for permeability testing.

Full-depth continuous core samples, 64 mm in diameter, were retrieved after the soil-cement mixture had hardened. Each core run was generally about 1 m in length and contained at least four test specimens with a length to diameter ratio of at least 2. The minimum specified recovery of 85 percent for each core run was achieved, except where soil-cement was produced in gravelly soils. Representative cores were generally retrieved 14 to 28 days after mixing.

### Test Section

Prior to full production one to two test sections were installed to verify that the required geometric tolerances, uniformity and design strengths could be achieved. For each grout-soil mix tested, at least four full-depth core samples were retrieved for inspection and testing.

### Production Soil Mixing

The walls were constructed using the same equipment; mix design, and procedures that were used for the test sections. The Contractor conducted sampling and testing of the production walls using the same equipment and methods employed during the test sections. During full production, one representative full-depth core sample was retrieved for every 150 lineal meters (approximately one core for each 80 panels) of CDSM installed.

### Daily Quality Control Report

Daily quality control reports were submitted generally 12 to 48 hours after installation. Each daily quality control report documented the progress of the wall construction and presented the results of the real-time monitoring of the mixing parameters for each panel installed. Results of subsequent core data and strength testing were submitted upon the completion of the strength testing, generally 28 days after installation. The daily quality control report included the following QC-monitoring parameters for each soil-cement panel: a) rig number, b) type of mixing tool, c) date and time of the panel construction, d) panel and column numbers, e) column diameter, f) column top and bottom elevations, g) grout mix design designation, h) grout specific gravity measurements, and i) description of the obstructions, interruptions, or other difficulties during the installation and how they were resolved. The daily quality control report also included the following real-time monitoring parameters for each column at 1.2 m intervals in tables: a) depth vs. penetration/withdrawal rates, b) depth vs. shaft rotation rate, c) depth vs. grout injection volume, d) depth vs. average amperage draw of the mixing motors.

## QUALITY CONTROL DATA

Soil mixing for the Berths 57/58 project and the Oakland Airport Roadway project was completed in May 2001 and February 2002, respectively. A total of 899 core runs were retrieved and observed, representing approximately 98,000 $m^3$ of soil-cement product installed for these two projects. The frequency distribution of the core recovery for 529 core runs recovered on the Berths 57/58 project is presented in Fig. 3.

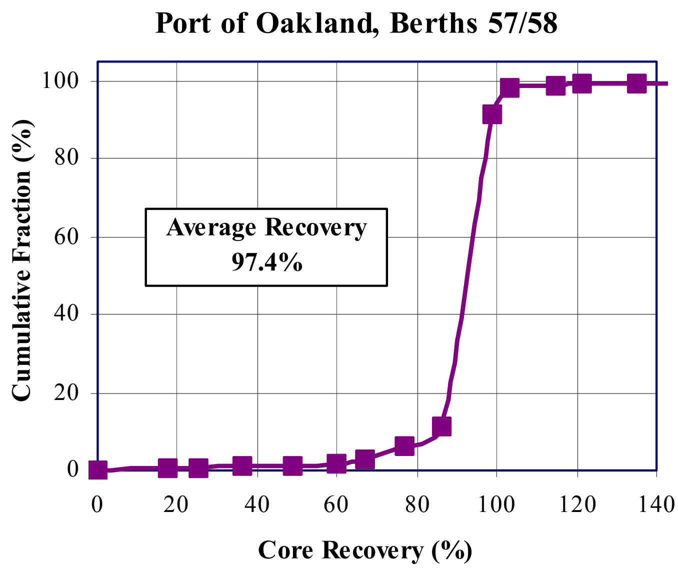


*Fig. 3. Percentage of core recovery Port of Oakland Berths 57/58 Project.*

The frequency distribution of the core recovery for 370 core runs recovered on the Oakland Airport Roadway project is presented in Fig. 4. The high recovery shown in Fig. 3 and 4 is itself an indication of soil-cement strength and uniformity. Core recovery greater than 100% occurred due to the retrieval of unrecovered sections of the preceding core run.

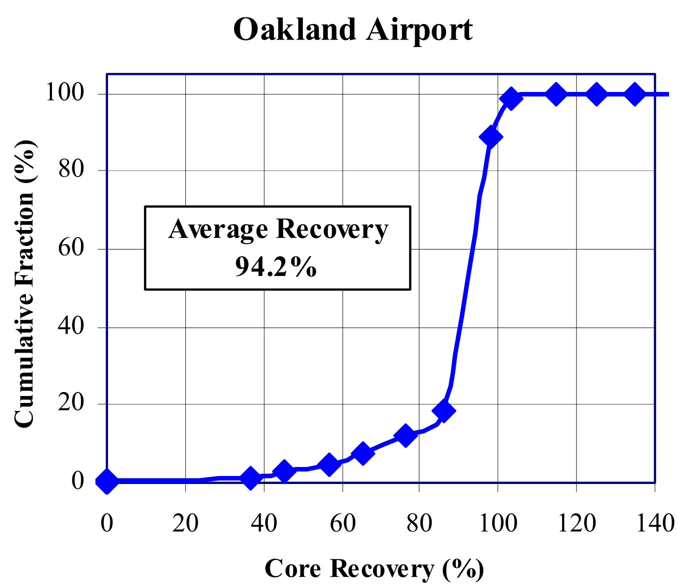


*Fig. 4. Percentage of core recovery Oakland Airport Roadway project*

Laboratory test results for samples tested on the Berths 57/58 project are presented in Fig. 5. The frequency distribution of unconfined compressive strength for these samples tested is presented in Fig. 7. Laboratory test results for samples tested on the Oakland Airport Roadway project are presented in Fig. 6. The frequency distribution of unconfined compressive strength for the samples tested is presented in Fig. 8.

Based on records of real-time monitoring of the installation parameters, geometric data from field surveys, and full-depth coring and testing data, it was determined that the soil-cement wall, grid, and block constructed met the geometric, strength, and uniformity criteria established for both the Berths 57/58 and Oakland Airport Roadway projects.

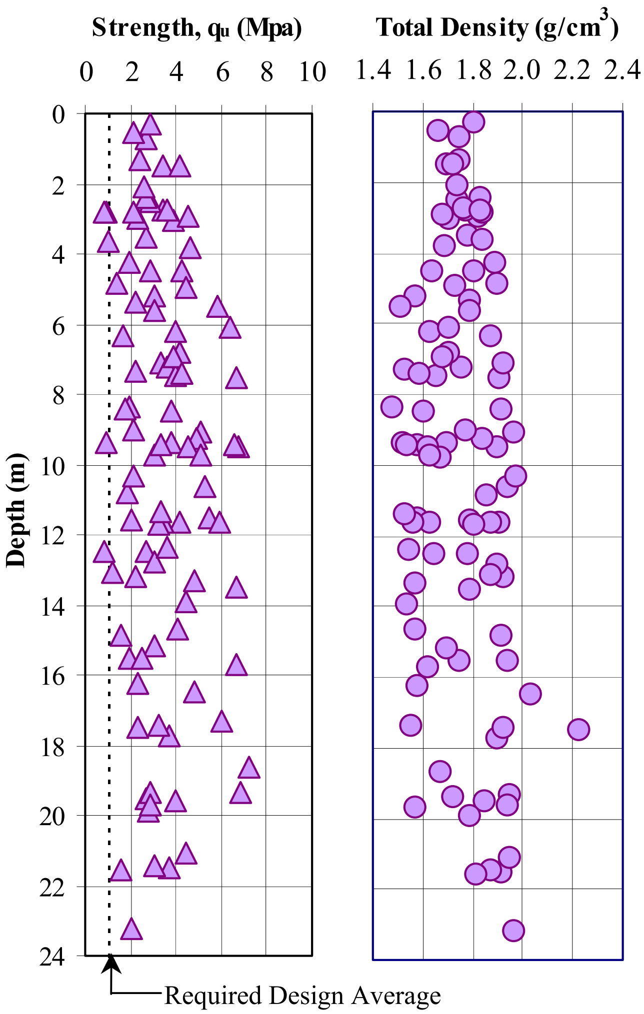


*Fig. 5. Laboratory testing results Berths 57/58 Project, Port of Oakland*

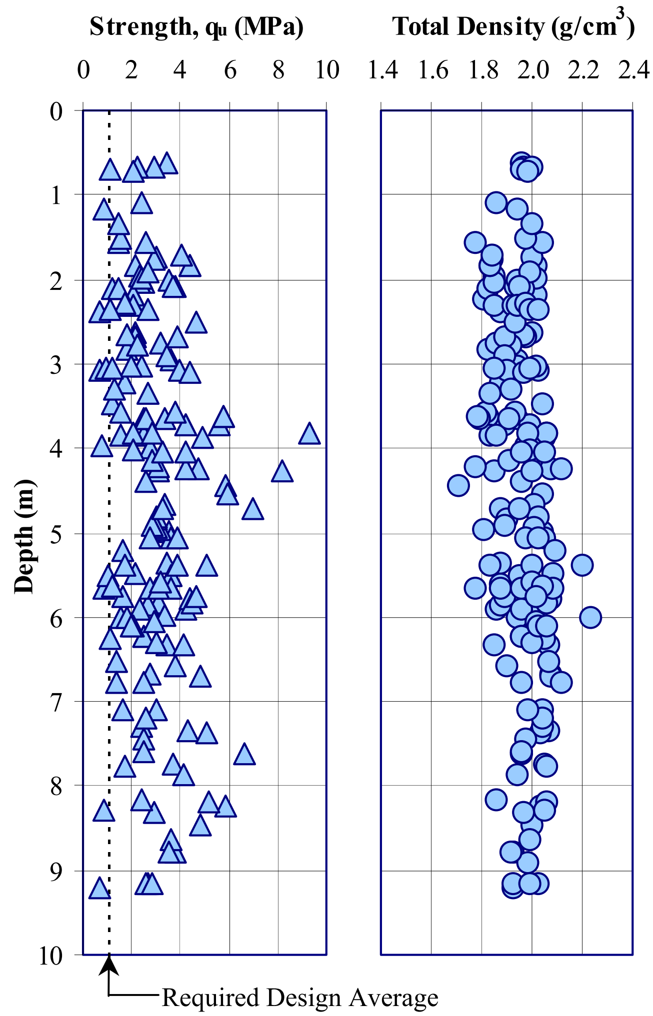


*Fig. 6. Laboratory testing results Oakland Airport Roadway project.*

Due to the inherent variation in the properties of in situ soils, and the impacts induced in the process of coring, transporting, and testing of the soil-cement samples, the strength of soil-cement has a wide range of distribution as shown in Fig. 5 to 8, despite the rigorous control of the installation parameters. This scattered distribution of the data matches with data from numerous projects in the United States and overseas. The mix designs for both projects were selected to satisfy the minimum strength requirement of 690 KPa, which in turn produced the distribution of strength as shown in Fig. 7 and 8 with an average value of 3.0 to 3.4 times that of the average strength used in the design. In other words, the minimum strength requirement supercedes the average strength requirement on which the design is based, and produces soil-cement with excessive strength.

The normalized curves of the strength distribution are presented in Fig. 9, and compared with the distribution curves from two sites with statistical control over the minimum strength: Five percent of strength test results are allowed to be lower than 60 percent of the average design strength. Statistical control recognized the natural distribution of

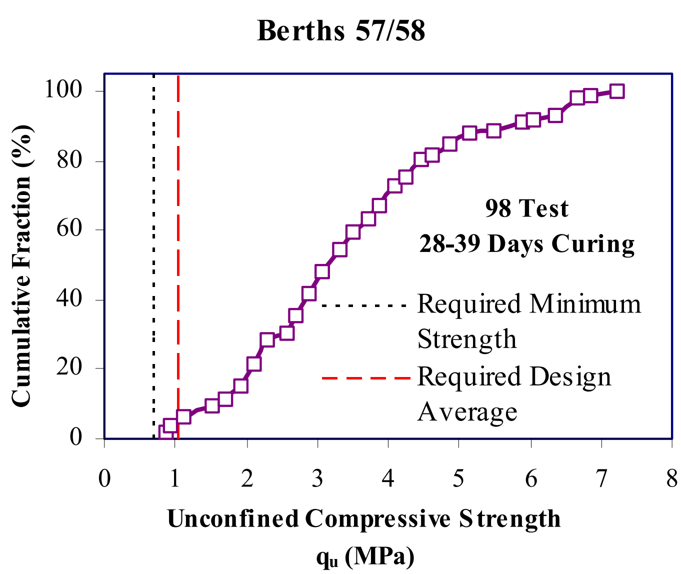


*Fig. 7. Strength testing results, Port of Oakland Berths 57/58 Project*

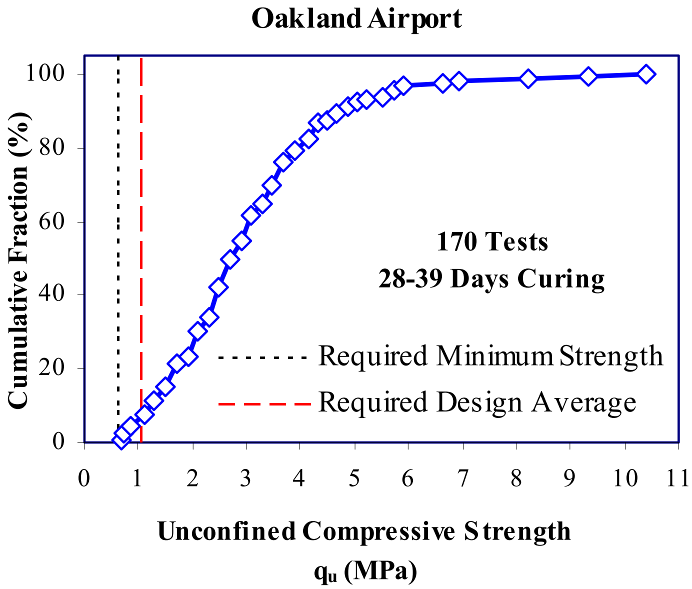


*Fig. 8. Strength testing results, Oakland Airport*

strength of soil-cement produced by in situ soil mixing and produced soil-cement with average values closer to the intended design average.

CONCLUDING REMARKS

The continuous refinement of CDSM equipment and quality control procedures enables the production of reliable soil-cement structures with various geometric designs to cope with specific project requirements. The application of the real-time quality control system maximizes the engineer's control over the installation parameters, and minimizes the uncertainties inherently associated with in situ soil improvement work. The specifications used for the Port of Oakland projects discussed in this paper enabled the production of high quality soil-cement structures. However, the requirement for maintaining a minimum at two thirds of the design average generates a high safety margin. The use of statistical control allowing 5 percent of the testing results below 60 percent of the design average would rationalize the safety margin and reduce the cost. Based on the extensive experience accumulated overseas and the successful implementation at nationwide project sites with various subsurface conditions to date, the deep mixing method is expected to gain increased acceptance as a practical and reliable tool toward the development of sites with challenging ground conditions.

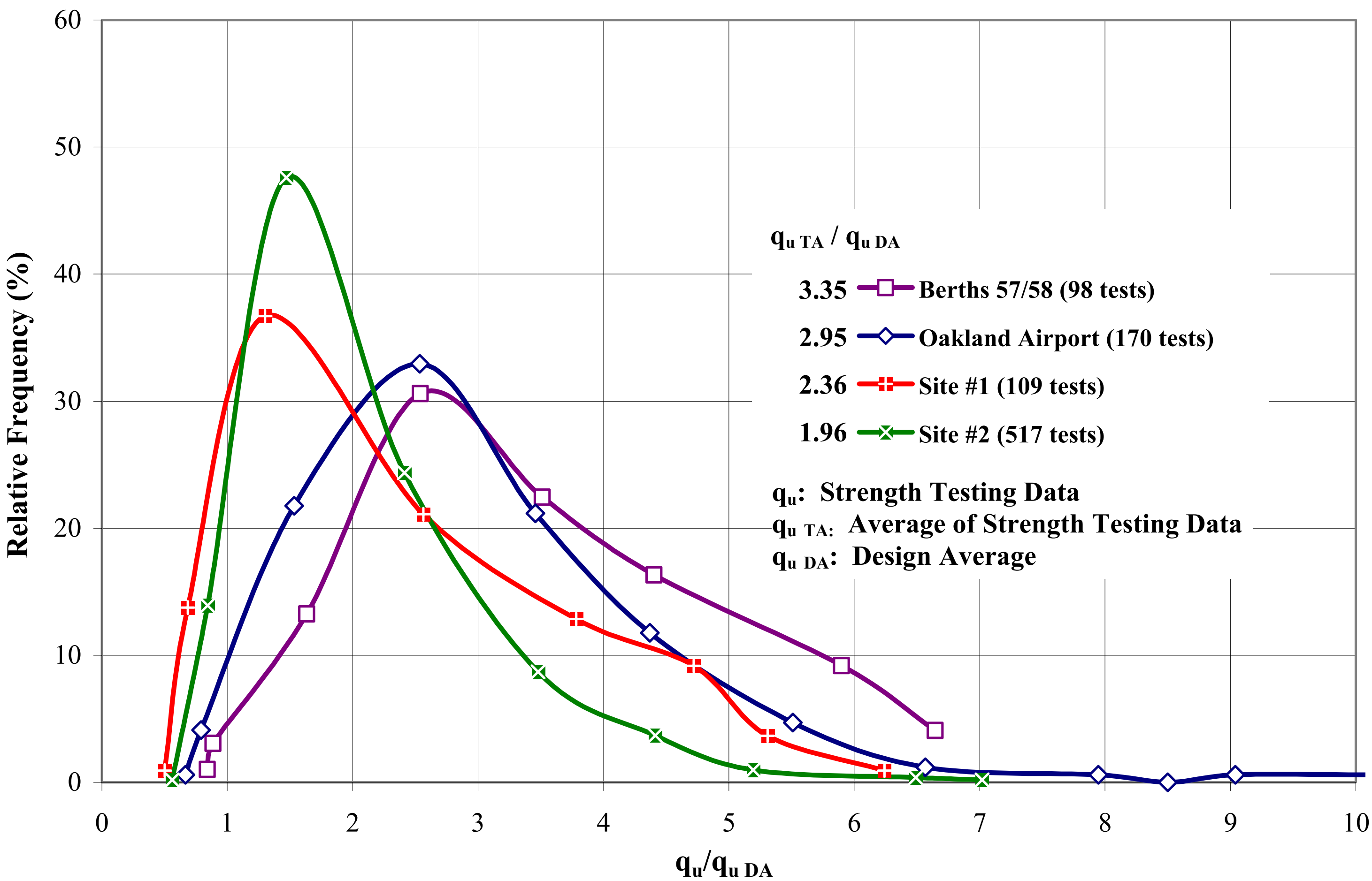


*Fig.9. Effect of Specification on Strength Distribution*

## REFERENCES

Geomatrix Consultants, Inc. (2000), "Final Report, Geotechnical Study, Marginal Wharf at Berths 57, 58, and 59, Port of Oakland, Oakland, California", pp. 24-29.

Herlache, W. A., Wu, S. M., Rudolph, R. W., Anderson, J. E., Serventi, G. M., Sakaida, V., and Yang, D. S. (1999), "CDSM Soil Stabilization for Berth Construction at Port of Oakland", Pre-conference Symposium on Ground Improvement and Geosynthetics, AIT 40th Anniversary Celebrations, November, Bankok, Thailand.

Yang, D. S., Scheibel, L. L., Lobedan, F., and Nagata, C. (2001), "Oakland Airport Roadway Project", Soil Mixing Specialty Seminar, 26th DFI Annual Conference, October, Clayton, Missouri, pp. 53-71.

Yang, D. S. (2003), "Soil-Cement Walls for Excavation Support", Earth Retention Systems 2003: A Joint Conference Presented by ASCE Metropolitan Section Geotechnical Group, The Deep Foundations Institute and The International Association of Foundation Drilling, May 6 and May 7, 2003. New York City, pp. 13-29.

## ACKNOWLEDGEMENT

The authors wish to recognize Mr. Gerald M. Serventi and Mr. Frank Lobedan at the Port of Oakland for their commitment to the application of new construction technology at the Port and for their valuable contributions during both the design and construction of these two projects.